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Renewable Energy Transition in India: Progress, Policies, and Persistent Challenges

***Dr. Sushant Kumar[1], Dr. Kapil Lakhera[2], Maitreyi Shah[3], Dr. Pooja Bahuguna[4], Radha Tripathy[5], Dr. Ramesh[6]**
[1]Assistant Professor, Department of Economics, HNBGU (A Central University), Uttarakhand, India
[2]Assistant Professor, Department of Humanities and Liberal Arts, DIT University, Uttarakhand, India
[3]Assistant Professor, Department of Economics, MPG College, Mussoorie, Uttarakhand, India
[4]Assistant Professor, Department of Economics, ITM College, Chakrata Road, Dehradun, Uttarakhand, India
[5]Reseach Scholar, Department of Economics, D.A.V (P.G.) College - Dehradun, Affiliated to HNBGU, Uttarakhand, India
[6]Assistant Professor, Department of Economics, DSB Campus, Kumaun University, Uttarakhand, India

***Corresponding Author Email ID:** skumar96272@gmail.com

Abstract
India's renewable energy (RE) sector has witnessed remarkable growth, driven by escalating energy demands, climate commitments, and strategic policy interventions. This study comprehensively reviews India's RE landscape, focusing on solar, wind, hydro, and biomass energy, while analyzing key government initiatives, achievements, and persistent challenges. Fossil fuels dominate India's energy mix (89.18 percent of primary consumption), but RE adoption is accelerating, with solar capacity expanding under the National Solar Mission (target: 100 GW by 2022) and wind energy reaching 41.93 GW by 2023. Hydropower and biomass contribute significantly, supported by policies like the Hydro Power Policy (2019) and National Biofuel Policy (2009). Despite progress, challenges such as technological gaps, financial constraints, land-use conflicts, and institutional inefficiencies hinder sectoral growth. A systematic review of literature (1990–2024) and gray sources (IEA, MNRE, NITI Aayog) underscores India's potential to meet its Paris Agreement targets (40 percent RE by 2030) but highlights the need for enhanced R&D, grid infrastructure, and public awareness. The study concludes with policy recommendations to bolster India's RE transition, ensuring energy security and sustainability.
Key Words: *Renewable energy, India, Solar power, Wind energy, Hydropower, Biomass, Policy challenges, Sustainable development, Climate change, Energy transition*

1.0 INTRODUCTION

Energy is fundamental to economic growth, social advancement, and industrial development worldwide. The 21st century has witnessed surging energy demands due to rapid industrialization and population growth, marking the Fourth Industrial Revolution (Fischer-Kowalski et al., 2019). Currently, global energy relies on fossil fuels (84%), nuclear power, and renewables (Mohr et al., 2015). Fossil fuels—oil (33%), coal (27%), and natural gas (24%)—remain dominant but face depletion (oil: 51 years; coal: 114 years; gas: 53 years) and contribute 91% of global emissions (Ritchie & Rosado, 2017; Hausfather & Friedlingstein, 2022). Nuclear energy offers a low-carbon alternative, yet risks like accidents (e.g., Chornobyl, Fukushima) and lifecycle emissions (mining, waste management) persist (Sovacool, 2008; Ohba et al., 2021). Despite safety measures, public concerns endure (Mileti & Peek, 2000). Renewable energy (RE)—solar, wind, biomass—presents a sustainable solution to climate change and fossil fuel dependence (Dabi & Saha, 2022; Vyas et al., 2022). Transitioning to RE is critical to mitigate global warming and ensure energy security (Dincer, 1998).

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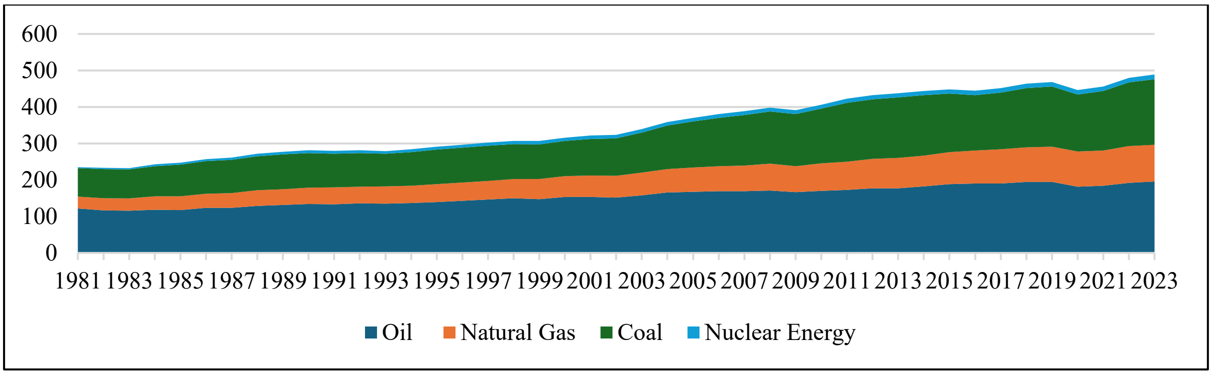
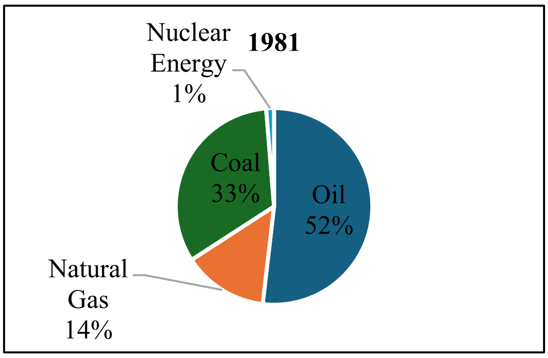


Figure 1: Total Fossil Fuels & Nuclear Energy Production in the World, 1981-2023 (EJ) (Energy Institute, 2024)



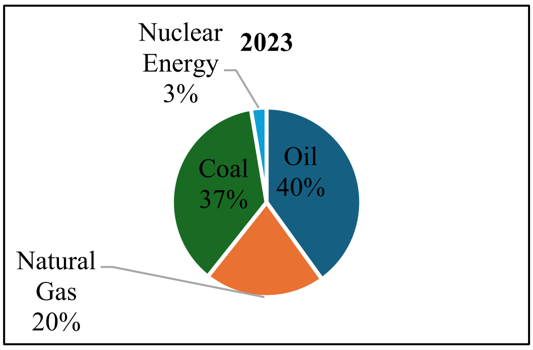


Figure 2: Share of World's Total Fossil Fuels & Nuclear Energy Production, 1981 and 2023 (Energy Institute, 2024)

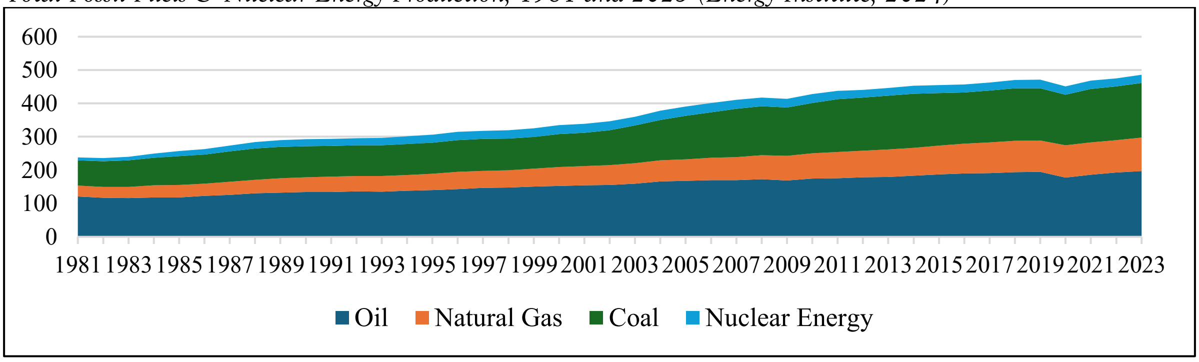
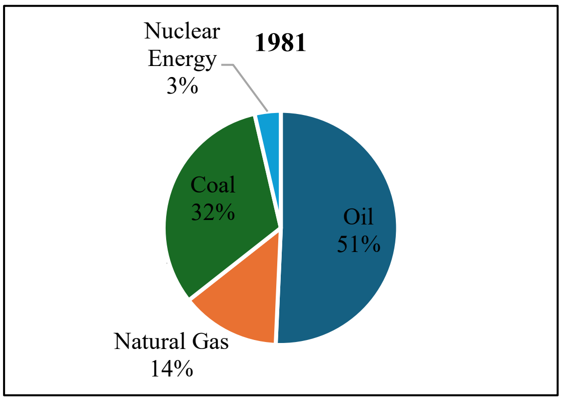


Figure 3: Total Fossil Fuels & Nuclear Energy Consumption in the World, 1981-2023 (EJ) (Energy Institute, 2024)



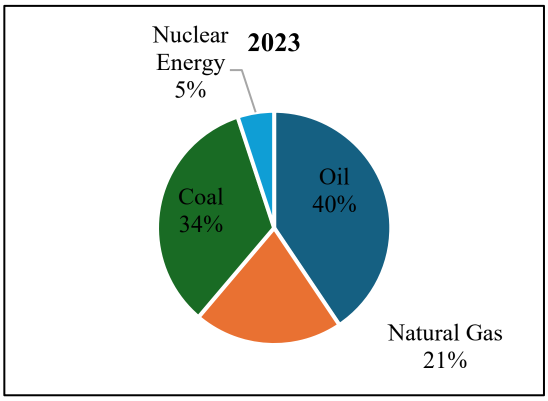


Figure 4: Share of World's Total Fossil Fuels & Nuclear Energy Consumption, 1981 and 2023 (Energy Institute, 2024)

2.0 RESEARCH METHODOLOGY

To thoroughly evaluate India's RE sector, a review was conducted using a database of white and gray literature spanning from 1990 to 2024. This review utilized a range of search keywords such as "Renewable", "Renewable Energy", "Renewable Energy Sector", "Renewable Energy in India", "Renewable Energy Sector in India", "Solar Energy" "Solar Energy in India", "Wind Energy", "Wind Energy in India", "Hydro Energy", "Hydro Power", "Hydro Energy in India", "Hydro Power in India", "Biomass Energy", "Biomass Power", "Biomass Energy in India", "Biomass Power in India", "Bioenergy", and "Bioenergy in India " to ensure comprehensive coverage. Our query was designed to find articles categorized as "Review," "Comprehensive Review," "Literature Review," and "Critical Review" to ensure thorough coverage of the topic. We focused on specific subject areas like environmental science, engineering, agriculture, social science, and earth science. Our search included only peer-reviewed articles and reviews published in reputable journals, ensuring high quality and credibility. Additionally, we restricted our search to English-language articles. We included only final versions of publications and open-access materials to provide a comprehensive and accessible set of high-quality, recent literature on India's renewable energy sector. The white literature was searched through a manual, systematic keyword search within the prominent Scopus database.

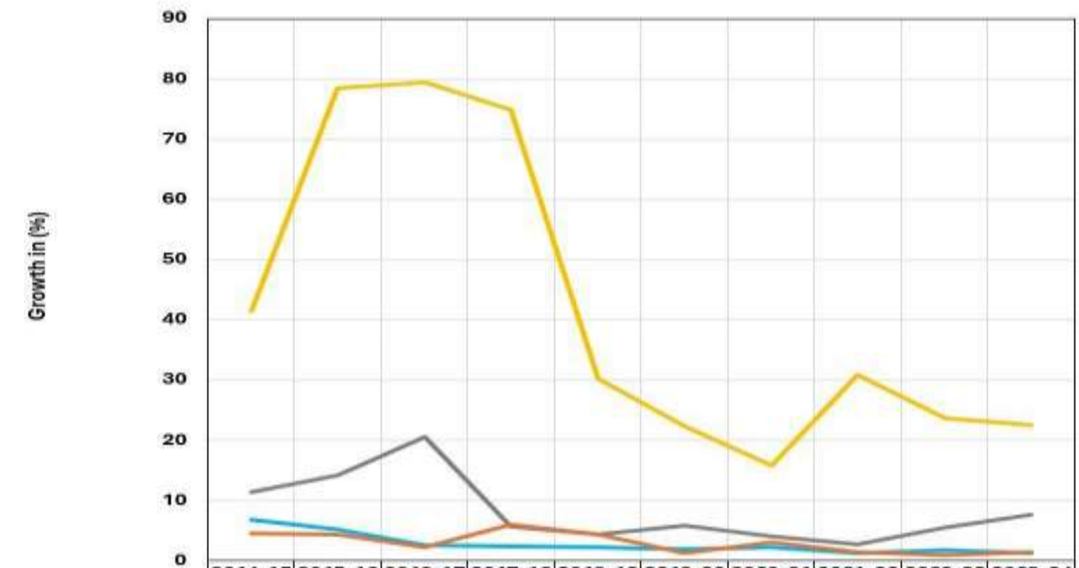
We manually searched gray literature to address the significant gap in the available literature. This search included energy statistics from the IEA, NITI Aayog, CEA, IRENA, IREDA, IPCC, EERE, and annual reports from various energy-related ministries of the GoI and other countries worldwide. Initially, we screened titles and abstracts to exclude irrelevant articles that (a) were published before 1990, (b) were not related to above given subject areas, (c) were not research articles or reviews, (d) published in languages other than English, (e) were not in their final published form, (f) were not from journal source, and (g) were not open access. The comprehensive review of RE in India is as follows:

3.0 Renewable Energy Landscape in India

As per the UN's World Population Prospects 2022 report, India's population will reach 1.043 billion in April 2023, surpassing China (UN DESA, 2022). This demographic shift underscores a rise in energy demand driven by higher consumption needs. India's primary energy consumption has grown by 4.2 percent annually from 2013 to 2023. It ranks third with a 6.2 percent share globally in primary energy consumption, following China (27.6 percent) and the USA (15.2 percent). In 2023, Its primary energy consumption comprised fossil fuels accounting for 89.18 percent, nuclear energy 1.10 percent, and renewable energy 9.66 percent. Due to its very high dependence on fossil fuels for energy consumption, India also ranks third globally in carbon dioxide emissions, with an 8.0 percent share, following China (31.9 percent) and the USA (13.2 percent) (Energy Institute, 2024). CO_2 is a GHG that significantly contributes to global warming (Friedlingstein et al., 2022; IPCC, 2022).

To ensure the conformity of nations worldwide, the UN supports the SDGs, which include satisfying present needs in a way that will enable other generations to meet their own. These aims have benefits for people, societies, small-scale businesses, and large enterprises, as well (Fallah Shayan et al., 2022). To retrench the effects of climate change, they recommend transitioning to RE sources to fulfill energy needs and reducing per-head energy intake (Santika et al., 2019). Several nations have aligned themselves with the SDGs by developing frameworks for adopting RE, establishing roadmaps to achieve their targets, and formulating specific policies for RE production. GoI think tank NITI Aayog has developed an all-encompassing index for India. This index provides a holistic picture of the country's social, economic, and sustainability levels. Additionally, NITI Aayog monitors India's and its states' progress towards achieving the SDGs (NITI Aayog, 2018). GoI created MNRE to advance alternative energy options to cater to the power deficit by meeting 500 GW of non-fossil-based electricity generation capacity by 2030 (PIB, 2024). India has vowed to ensure that by 2030, forty percent of its power generation will come from RE sources, as it is committed to creating a healthier living environment under the Paris Agreement (UNFCCC, 2015). The country possesses substantial, yet largely untapped, RE resources.

Figure 5: Year wise Growth (%) in Installed Capacity



	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21	2021-22	2022-23	2023-24
Small Hydro Power	6.84	5.17	2.58	2.51	2.23	1.96	2.35	1.25	1.86	1.21
Wind Power	11.41	14.25	20.54	5.79	4.33	5.92	4.00	2.83	5.62	7.65
Bio-Power	4.52	4.33	2.24	6.03	4.45	1.29	3.03	1.42	1.03	1.39
Solar Power	41.49	78.45	79.49	74.88	30.20	22.34	15.84	30.94	23.67	22.51

(Moosavian et al., 2013). In India, PV systems dominate the solar market, primarily due to challenges associated with solar thermal plants, such as a lack of reliable DNI data, high installation and operational expenses, and the need for water, which is similar to that required for coal-based thermal plants (Kumar et al., 2017).

3.1.2 Historical Background

Different reforms have been applied since Indian independence in 1947 to boost the country's solar power growth. Notably, after the oil crises between 1973 and 1977, GoI instituted several policies, programs, and institutions to promote solar power development. This led to the formation of NFP in 1973 and WGEP in 1979, which recognized the significance of RE. In 1982, the DNES was created, later renamed the MNRE during the energy sector liberalization in the 1990s. The ERC Act of 1998 was introduced to separate the public sector from tariff regulation and to encourage greater private-sector involvement (Yenneti, 2016). The CERC and SERC were established to fix tariffs and create guidelines for the energy sector (Mukherjee et al., 2017). However, launching the Electricity Act in 2003 mandated the adoption of RE. The act included an RPO, which required each state to obtain a minimum of 5 percent of its power from renewable supplies by 2010, with an annual growth of 1 percent over the following decade, aiming for a 15 percent share by 2020 (Sant et al., 2009). The JNNSM, launched in 2010 under the 'Solar India' initiative, aimed to encourage sustainable development and enhance India's energy safety. It contributed to global climate change efforts and endeavored to establish India as a pioneer in solar power by making favorable policies for rapid deployment. The Mission was divided into three phases: 2012-13, 2013-17, and 2017-22. The original goal was to achieve 20 gigawatts of grid-connected and 2 gigawatts of off-grid solar power capacity by 2022, which was later updated to target 100 gigawatts of grid-connected capacity by the year 2021-22 (Singh & Idrisi, 2020; Upadhyay & Singh, 2021).

3.2 Wind Energy

3.2.1 Overview

In recent years, clean energy sources, such as solar, wind, etc., have gained significant importance due to their minimal environmental impact, which is generally much lower than fossil fuels. Wind power has become one of the expanding RE sources compared to other clean energy options (Li et al., 2011; Ragaert et al., 2017; Wüstenhagen et al., 2007). The wind energy conversion system is a comprehensive setup that includes wind turbines, generators, control mechanisms, and integration methods. WTs transform the energy of the wind into power, with their effectiveness determined by how much power is produced at the rotor with the overall power available in the wind flow (Chaudhuri et al., 2022). Over the two decades, there has been growth in the demand, production, and supply of wind energy, specifically in European and Asian nations (Chaurasiya et al., 2019; Dawn et al., 2019) including India.

3.2.2 Historical Background

The idea of utilizing wind energy in India originated in 1952 when the CSIR started collecting and analyzing data on surface winds and their durations to find suitable locations. From the 1960s to the 1980s, extensive surveys were conducted by the NALs and CSIR to refine the estimates of wind energy potential. This eventually led to the development of the initial demonstration wind farms in 1986 in Ratnagiri (Maharashtra), Okha (Gujarat), and Tirunelveli (Tamil Nadu), which were equipped with 55 kilowatts Vestas WTs. Despite these initiatives, the total installed wind power capacity remained at 220 megawatts until 2000 (Mani, 1990). Wind energy installations in India saw significant growth after 2002, escalating from a mere 1.6 GW to 41.93 GW by 2023. This comprised 25 percent of the total installed RE capacity for FY 2022-23 (MNRE, 2023).

3.3 Hydro Power

3.3.1 Overview

Hydropower utilizes the energy from moving or descending water, making it a RE source. It is one of the earliest and most prevalent methods of RE worldwide. These plants transform the kinetic energy of water into mechanical energy via turbines, which then produce electrical energy through generators (IRENA, 2012). Hydropower is the leading RE source, generating nearly 16 percent of the world's electricity and over 80 percent of the world's RE. It is vital for the energy supply in more than 150 countries, with over 25 countries depending on it for 90 percent of their electricity. Hydropower is also the only large-scale, cost-efficient, and flexible power generation and storage technology capable of meeting demand fluctuations rapidly and storing energy for extended periods, making it a reliable and efficient RE source (Wilson, 2015).

3.3.2 Background

Hydropower development in India began with establishing a small station in Darjeeling in 1897. The first significant hydropower station aimed at industrial development was set up in 1902 at Sivasamudram on the Cauvery River, starting with a capacity of 7.92 MW, which expanded to 47 MW by 1938. This station initially supplied power to the Kolar Gold Fields and later to Bangalore and Mysore. Other early developments include the 4 MW Mohora hydro station in J&K in 1905 and several stations established by the Tata industrial group in the Western Ghats, notably Khopoli, Bhivpuri, and Bhir. 1947, India's installed hydro capacity reached 508 MW, with key projects like the Jogindernagar and Pykara hydro stations contributing significantly. After independence, major multipurpose projects like Bhakra Dam, Rihand Dam, and Sharavati were undertaken, increasing hydro capacity to 1,920MW by 1960. A systematic study by the CWPC in the 1950s initially estimated the country's hydro potential at 42 100 MW, later revised by the CEA to 84 044 MW (Gopalakrishnan, 2015).

3.4 Biomass Power

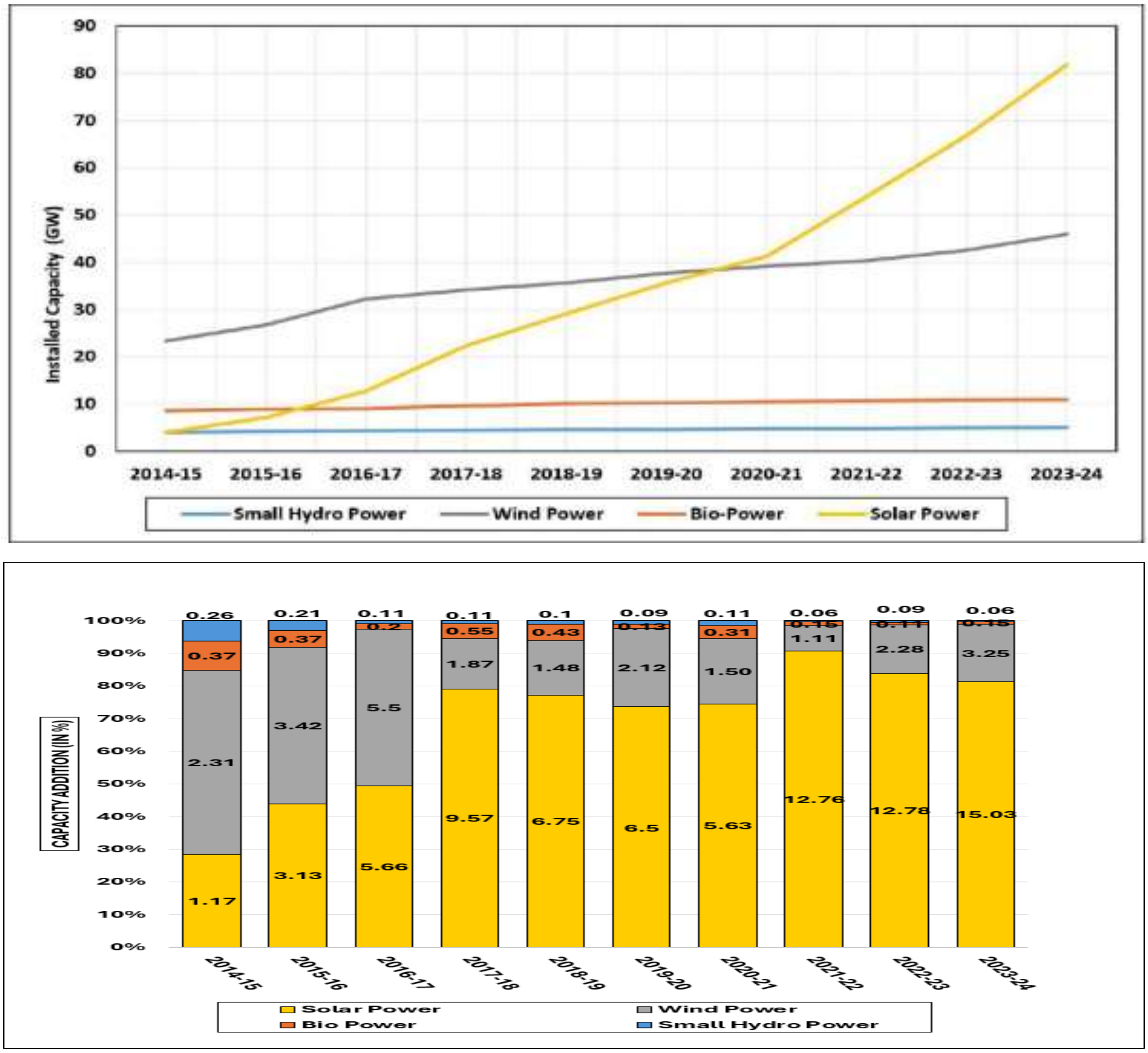
3.4.1 Overview

Biomass is an energy source obtained from plant materials, including agricultural residue (such as crop waste and animal manure), forest resources, specifically grown energy crops (like algae, perennial grasses, and woody crops), urban wood waste, and food waste. This unique RE source can be transformed into fuels, chemicals, or power (Batidzirai et al., 2012; Haberl et al., 2010; Hoogwijk et al., 2003; EERE, 2020). Biomass is generated when plants capture CO_2 from the atmosphere during photosynthesis. When biomass is burned, the CO_2 is released back into the air, where plants can reabsorb it in the next growing cycle. This makes biomass a renewable resource on a relatively short time scale. If appropriately managed, bioenergy has the potential the potential to significantly increase its contribution to the global energy supply, reduce GHGs, and offer additional environmental benefits (Sadrul Islam & Ahiduzzaman, 2012).

3.4.2 Background

India has a rich history of strategizing its energy resources, with biogas and improved cook-stove programs dating back to the 1940s. Rural electrification and afforestation began in the 1950s. The NBP emerged in the 1970s as part of rural and RE policies in response to a rural energy crisis exacerbated by rising oil prices, increased energy demand, wood trading, and overexploitation of biomass resources. By the late 1970s, India started promoting RE technologies, with biomass being a key focus due to its local availability and sustainability (Shukla, 1997). The Electricity Act 2003 promotes RE, including biomass, through provisions like The RPO and preferential tariffs. The amended National Tariff Policy 2016 mandates that Distribution Licensees procure 100 percent of power from waste-to-energy plants. The GoI introduced policies in 2017 and 2018 to encourage biomass co-firing in coal-based PPs and declared power from biomass co-firing as renewable in 2019. Additionally, biogas use in vehicles was included in the Central Motor Vehicles Rules in 2015. The NBP 2018 aims to increase ethanol blending in petrol to 20 percent by 2025-26 (IEA Bioenergy, 2021).

Figure 6: Trend in RES Cumulative Installed Capacity



Source: Renewable Energy Statistics 2023-24 (p. 16), by Government of India, Ministry of New & Renewable Energy, 2024*

4.0 KEY GOVERNMENT INITIATIVES AND ACHIEVEMENTS

India's commitment to RE has been bolstered by several proactive government initiatives to harness its vast renewable resources. These initiatives span various sectors, including solar, wind, hydro, and bioenergy, aiming to make the country a world leader in sustainable energy. Here are some key initiatives driving India's RE growth:

4.1 Solar Energy

4.1.1 National Solar Mission (NSM) – 2010

On June 30, 2008, the GoI introduced the NAPCC, which outlines eight primary National Missions designed to tackle climate change. These missions include the NSM, the NMEEE, the NMSH, the NWM, the NMSHE, the NMGE, the NMSA, and the NMSKCC (PMCCC, 2008; Rattani, 2018). Launched by the MNRE in 2010, the NSM aimed to deliver clean and green energy to the nation. The initial goal was to reach twenty gigawatts of grid-connected by 2022. However, on June 17, 2015, this goal was revised to a hundred gigawatts, with sixty gigawatts coming from large and medium land-based projects and forty gigawatts from rooftops. Additional objectives included installing twenty million solar lighting systems, creating twenty million square meters of solar thermal collector area, promoting solar cell and module manufacturing, and attaining grid parity through research and development support. The mission is structured in three phases, each divided into batches and tranches, allowing for a gradual process that shields the government from potential subsidy costs due to inflation or decreasing costs (CERC, 2008; Deo & Shrikant, 2005; TERI, 2008).

4.1.2 Development of Solar Parks and Ultra Mega Solar Power Projects – 2014

The "Development of Solar Parks and Ultra Mega Solar Power Projects" scheme was introduced on December 12, 2014, with an initial target capacity of twenty GW, which was later increased to 40 GW on March 21, 2017. This scheme aims to establish a minimum of 50 Solar Parks by the 2023-24 period. These Solar Parks are large areas designed with the necessary infrastructure and clearances to support solar projects, typically with capacities of 0.500 GW or more. However, smaller parks, with capacities of up to 0.020 GW, are also considered in regions with limited non-agricultural land. Each park generally requires 4 to 5 acres of land per MW (MNRE, 2023).

4.1.3 Off-Grid & Decentralized Solar PV Applications Scheme – 2018

The scheme launched in August 2018 aimed to install 300,000 streetlights, 2.5 million study lamps, and hundred megawatts of off-grid solar PPs by 31st March 2021. It provided thirty percent CFA of the system's benchmark cost for general category states and 90 percent for NE states. Additionally, solar lamps for the study received 85 percent support from the central government in NE states and areas affected by LWE (MNRE, 2023).

4.1.4 One Sun One World One Grid (OSOWOG) – 2018

The OSOWOG initiative, proposed by PM Narendra Modi at the ISA Assembly in October 2018, aims to connect energy supplies across borders, promoting the idea that "the sun never sets." The initiative envisions linking regional grids to transfer RE, particularly solar power (ISA, 2022). In 2021, the governments of India and the UK combined the UK's Green Grids Initiative (GGI) with the OSOWOG endeavors to link 140 nations through a global network of solar power grids. This initiative enhances the viability of solar projects, reduces storage needs, supports the Paris Agreement targets, and represents a significant investment in low-carbon energy. Additionally, it promises economic benefits by lowering living costs and improving livelihoods (ISA, 2023).

4.1.5 PM – Kisan Urja Suraksha Evam Utthaan Mahabhiyan (PM – KUSUM) Yojana – 2019

The scheme was launched in March 2019 as an initiative to enrich energy protection for agrarians in India while boosting the portion of clean energy capacity to forty percent by 2023. The scheme is divided into three main components. Component A – establishes 10 GW of RE PPs on unused land, with individual plants ranging from 500 KW to 2 MW. Component B – deploys 2 million independent solar-powered pumps for off-grid regions to replace diesel pumps, with a capacity of up to 7.5 HP, and Component C – converts 1.5 million grid-connected agricultural pumps to solar power, enabling farmers to use and sell surplus solar energy to DISCOMs. (Chateau et al., 2023).

4.1.6 R&D in Solar Energy

The MNRE-NCPRE at IIT Bombay, initiated in 2010, plays a crucial role in India's 100 GW solar mission. Phase I (2010-15) and II (2016-21) have significantly contributed to R&D and educational support. Similarly, the CSIR-NPL, a pioneer in silicon photovoltaics since the mid-1970s, focuses on advanced solar technologies like organic and perovskite cells. They also develop waste management solutions for recycling solar modules and electronic waste, enhancing sustainability in the solar sector (MNRE, 2023).

4.2 Wind Energy

4.2.1 R&D in Wind Energy

India is fostering offshore wind energy growth through met-ocean measurements at the Gulfs of Khambhat and Mannar. This project, aimed at assessing wing resources and oceanographic parameters, has pioneered integrated floating buoy LiDAR technology in India. This technology enhances offshore wing measurement cost-effectively along the 7600 km coastline, identifying high-capacity utilization zones. Similarly, the IWSRA has produced valuable maps and data reports, aiding policy revision and identifying potential hybrid energy sites. The initiative has also contributed to skill development among developers, enabling the implementation of wind-solar hybrid systems. NIWE has developed and validated wind potential and hybrid maps, utilizing advanced techniques to improve accuracy. Additionally, publications like the study on wind speed variability enhance understanding and stakeholder confidence in India's wind energy potential. (MNRE, 2023).

4.3 Hydro Power

4.3.1 Indian Government Boosts Hydro Power

The GoI launched several initiatives in March 2019 to boost the hydropower sector:

- LHP projects over 25 MW were classified as RE sources.
- A separate HPO was created within the NRPO.
- Measures to rationalize tariffs were introduced to lower hydropower costs.
- Budgetary support was allocated for flood moderation and storage hydroelectric projects.
- Financial assistance was provided for critical infrastructure.

These steps aim to reduce capital costs and project tariffs in the initial years, enhancing project viability and marketability (MoP, 2023).

4.4 Biomass Power

4.4.1 National Biogas and Manure Management Program (NBMMP) – 1982

The NBMMP, which was launched in 1981-82, aimed to establish small biogas plants for family use and was initially called the NPBD. The program expanded during the 11th FYP (2009-12). In 2009, the CCAE approved Rs. 562.89 crores for the program, providing incentives of Rs. 16 700 per unit in NE states and Rs. 10,000 per unit elsewhere. By March 2013, approximately 4.5 million family-type biogas plants had been established with central subsidies since 1981-82 (Joshi et al., 2016).

4.4.2 National Biofuel Policy (NBP) – 2009

India's NBP announced on December 24, 2009, that it aimed to boost the energy sector's growth by promoting RE use and mandating alternative fuels in transportation. The policy targeted a 20 percent replacement of petroleum fuels with biofuels by the end of the 12th FYP (2012-17). The government reinforced this commitment by implementing the Ethanol Blending Program, mandating 5 percent ethanol blending in gasoline, as decided in the Cabinet Committee of Economic Affairs meeting on November 22, 2012 (Joshi et al., 2016).

5.0 CHALLENGES FACING THE RENEWABLE ENERGY SECTOR IN INDIA

5.1 Technological Challenges

- On December 11, 2017, the MNRE issued a policy for standardizing RE projects, covering testing, standardization, and certification aspects. However, these standards remain at a basic level compared to international practices.

- Quality assurance processes are still in their initial stages, and advancements in RE largely depend on robust action plans for establishing standards, testing procedures, and performance certification.
- Currently, there is a lack of clear documentation concerning testing laboratories, referral institutes, review mechanisms, inspection protocols, and monitoring processes.
- The country has limited R&D centers focused on RE, and efforts to increase investment in R&D are insufficient.
- Dependence on international suppliers for equipment and technology is high, and locally manufactured spare parts are scarce.

5.2 Financial Challenges

- Budgetary constraints such as delayed fund allocation and insufficient budgets hamper the sector's advancement.
- High initial capital costs for renewable projects compared to fossil fuels pose significant financing challenges.
- PPAs often feature predetermined fixed tariffs higher than current bids, creating financial discrepancies.
- Investors perceive the renewable sector as risky due to its lower gross returns.
- Investors view renewable projects as risky and prefer experienced contractors, established suppliers, and operators.
- Poor performance of renewable projects further exacerbates financial challenges, risking funding availability.

5.3 Environmental Challenges

- Expansive land is necessary for large-scale solar installations, which can lead to land degradation and loss of natural habitat.
- The manufacturing of PV cells involves hazardous chemicals, exposing workers to risks like silicon dust, which poses significant health concerns.
- Additionally, the disposal of manufacturing waste is often inadequate, and using toxic materials in thin-film PV cells raises environmental and public health concerns.
- Although a single wind turbine occupies little space, the required spacing between turbines for efficiency and the infrastructure needed (road and transmission lines) significantly increases land use.
- Offshore wind turbines, more significant than their onshore counterparts, require substantial space and can impact marine activities such as fishing and sand extraction. They also affect marine wildlife, including fish and other sea creatures.
- Hydroelectric turbines can harm aquatic ecosystems by killing fish and other organisms. Furthermore, insufficient control of aquatic plants and weeds exacerbates ecological damage.

5.4 Training and Awareness Challenges

- The RE sector suffers from a lack of skilled professionals and faces a significant workforce deficit.
- After the installation of RE projects, there is insufficient follow-up or support for ongoing maintenance. This extends to a shortage of trained personnel for demonstrating, operating, and maintaining these systems.
- There is a general deficit in knowledge about RE technologies, coupled with a lack of awareness programs for the public. This ignorance hinders efforts to acquire land for renewable projects, as many landowners, particularly in agriculture, are reluctant to lease their land for such purposes.

5.5 Institutional Challenges

- Institutes, agencies, and stakeholders under the MNRE often exhibit poor inter-institutional coordination, which hampers progress in RE development. This lack of cooperation and coordination, along with delays in policy implementation, reduces investor interest.
- The single window project approval and clearance system is unreliable and often delays project clearances, leading to penalties for developers.
- There is an insufficient workforce in ministries, institutes, and agencies.

- Proper research centers for renewable infrastructure development are lacking, as are customer care centers to guide developers (IEA & NITI Aayog, 2021; Kumar & Majid, 2020).

6.0 DISCUSSION AND CONCLUSION

This discussion highlights India's substantial progress in the RE sector through diverse initiatives across solar, wind, hydro, and biomass energy. The NSM and the development of solar parks have significantly advanced solar capacity, positioning India as a global leader in solar power. Wind energy has seen remarkable growth since the early 2000s. India now ranks fourth globally in installed wind capacity, bolstered by the National Offshore Wind Energy Policy and wind-solar hybrid strategies. Hydropower, with a rich history dating back to 1897, continues to contribute significantly to India's RE landscape, supported by recent policy measures to boost large and small hydro projects. Biomass energy, leveraging the country's agricultural residue and waste, has also seen considerable development, supported by various policies such as the NBMMP. Despite these advancements, challenges persist, including technological constraints, limited grid infrastructure, and policy implementation issues. Technological innovations and standardization are crucial for maintaining quality and efficiency in RE projects. Furthermore, addressing infrastructure and regulatory hurdles will be essential to sustain and accelerate the growth of India's RE sector. Integrating these renewable resources is vital for achieving climate goals and fostering sustainable development. As India continues to expand its RE capabilities, the focus must remain on overcoming these challenges while leveraging technological advancements and policy frameworks to ensure a robust and resilient future.

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Conflict of Interests

The authors declare no conflict of interest related to this research.

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